# Fluctuations of Mid-to-High Frequency Acoustic Waves in Shallow Water

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## LONG-TERM GOALS

The long-term goal of this project is quantitative understanding of the physics governing the broadband frequency (50 Hz to 50 kHz) acoustic signal propagation, reflection, refraction and scattering in shallow water and coastal regions in the presence of temporal and spatial ocean variability. The complications presented by this variability in the ocean and the seabed environment are significant and must be considered for application development.

## OBJECTIVES

Scientific objectives of this research are to understand the acoustic wave propagation in a dynamic environment in two different frequency bands. One band is from 50 Hz to 500 Hz and the subject of interest in this band is to assess the effect of environment anisotropy on the propagation and to separate different effects due to horizontal refraction and mode coupling, from adiabatic regimes. This frequency band is referred to as low frequency. The other frequency band of interest is from 500 Hz to 25 kHz which coincides with the band used for the underwater communication and the subject of interest in this band is to assess the effect of water column as well as the sea surface variability on the propagation. This frequency band is referred to as mid-to-high frequency band.

## APPROACH

Combined experimental and modeling efforts have been utilized in our research to gain understanding of the broadband acoustic wave propagation in our research. Studies carried out in the low frequency band use the SWARM-95 field data. Theoretically, we have investigated the structure of the continuous and trapped horizontal (x-y plane) modes, which are created in-between the internal wave fronts. Both ray and PE representations were used. Modal scintillation index has been obtained as a function of frequency. The horizontal modal representation has produced additional insights into the physics of this ducting effect.

The high frequency band part of our research is based on the field data collected during the Kauai Experiment in 2003. The oceanographic variability such as the current profile and the sea surface wind waves are important parameter for assessment of the forward problem in this regime. A combined ocean-surface model that was developed in our earlier studies has been used to analyze the data. Deterministic features of the acoustic wave propagation are identified and separated for further modeling.  The key participants in our research efforts at the University of Delaware are Dr. A. Song

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14. ABSTRACT
**The long-term goal of this project is quantitative understanding of the physics governing the broadband frequency (50 Hz to 50 kHz) acoustic signal propagation, reflection, refraction and scattering in shallow water and coastal regions in the presence of temporal and spatial ocean variability. The complications presented by this variability in the ocean and the seabed environment are significant and must be considered for application development.**

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(Post Doctoral Fellow), Mr. A. Sundberg (Field Engineer), and Mr. J. Luo (Graduate Student). We have been collaborating with the following colleagues in other institutions, J. Lynch (WHOI), W. Siegmann (RPI), B. Katsnelson (UV), M. Porter (HLS Inc.), and D. Rouseff (APL).

**WORK COMPLETED**

Progress has been made in understanding the three-dimensional (3-D) effect of low frequency propagation in shallow water in the presence of internal waves [1, 2]. The effects due to the horizontal refraction are separated from those due to mode coupling and adiabatic conditions. Based on these results a hypothesis is developed for further investigation and a field experiment has been designed to test the theory. In the high frequency band, we have continued analysis of the Kauai-2003 experimental data. In addition to addressing the physics of high frequency acoustic we have developed a new decoder for underwater communication. In addition, for instrumentation we advanced our Data Acquisition Unit (DAU) design to eliminate the signal to noise ratio problems that we had. We conducted a multi-institutional field experiment with the new system in summer 2005 (Makai Experiment) and have done a preliminary quality check on the data.

**RESULTS**

We have made a higher understanding in propagation of 50-500Hz and 8 kHz to 24 kHz frequency bands. In the following section a brief highlight of each area is provided.

**A- Broadband propagation in presence shallow water internal waves**

When broadband acoustic signals propagate through Internal Solitary Waves (ISW), time-integrated intensity fluctuates with periods close to that of the ISW. Depending on the source-receiver geometry, the orientation of the internal wave front with respect to the acoustic track, and other parameters of the waveguide such as the ratio between the thermocline layer thickness and the water depth, this effect could be significant (as large as 10 dB in an experiment conducted on the New Jersey Continental Shelf in 1995). Intensity fluctuations are largely synchronous in water depth, so that the total signal energy in the water for a given time remains the same for all depths. These features are interpreted as manifestations of 3-D refraction in this shallow-water waveguide. To explain this phenomenon a theoretical model based on horizontal rays and vertical modes is used [1]. The concept of scintillation index (SI) is defined for a given mode and frequency. This quantity characterizes the average fluctuations for a period when internal waves are active in the waveguide.

Figure 1 shows the passage of an internal wave front during two consecutive hours measured during the SWARM experiment. A well defined regime during the first hour is changing into a less defined ocean structure during the second hour.
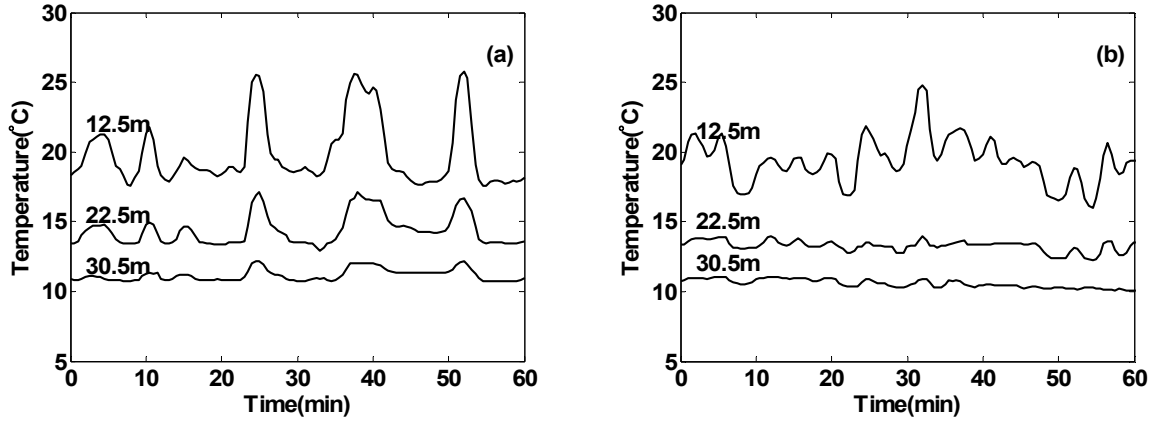
*Figure 1. Recorded temperature data at WHOI vertical array on August 4, 1995. (a) From 19:00:00 to 20:00:00 GMT, (b) From 20:00:00 to 21:00:00 GMT.*

Using the broadband experimental data transmitted during the two hours from two sources, one placed above and the other below the thermocline, the modal scintillation index for the first four modes is constructed and is shown in Fig. 2. The frequency dependent behavior of this parameter characterizes the average fluctuations for different waveguide modes and it is an indicator of interaction between medium inhomogeneity and acoustic signal [2]. In the first hour when a well defined ISW is present (Fig. 2), the amplitude of SI for mode 1 is less than all other three modes except for frequencies > 200 Hz. During the second hour, SI amplitude for mode 1 (while less than SI for mode 2 for all frequencies), falls below mode 3 for frequencies < 100 Hz and follows a more complicated behavior for other frequencies.
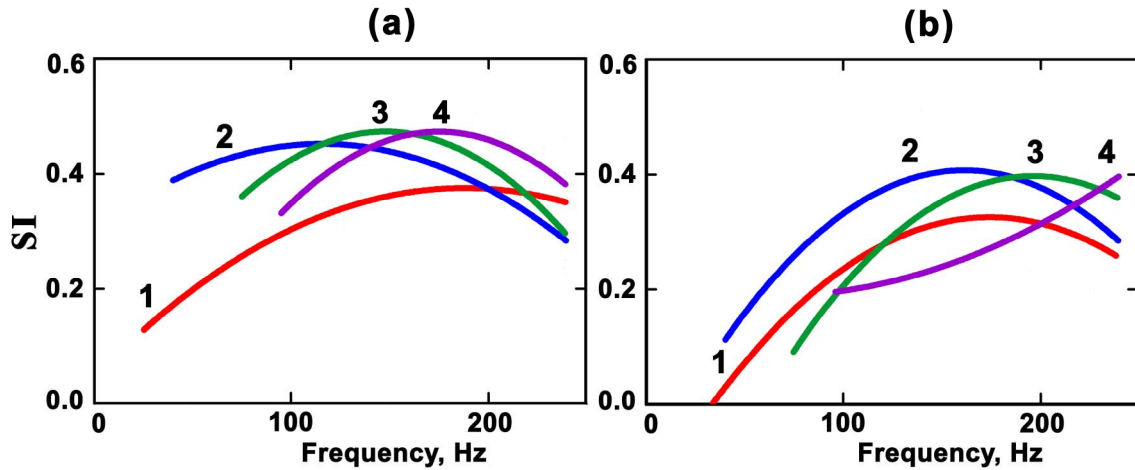


*Figure 2. Frequency dependence of modal scintillation index SI (f) obtained from SWARM data during two different oceanographic conditions: (a) T=19:00-20:00 GMT, and (b) T=20:00-21:00 GMT on Aug. 4, 1995 [2].*

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## B- Ocean variability effects on high-frequency acoustic propagation

Variability of ocean physical parameters can cause significant fluctuations in the propagation of broadband acoustic signals in shallow water. The arrival time of energy following a particular ray path depends on sound speed, current profile through which the ray passes, and on roughness of the ocean boundaries with which reflects or scatters. The sea-surface fluctuations may induce fast fluctuations in the acoustic signal propagation while temporal variability of the sound speed and current profile may induce large-scale fluctuations. It is desirable to resolve both these variability scales, hence we consider different sampling of the ocean on both short and long geophysical time scales.

The Kauai Experiment was conducted in 2003 with the objective to study high-frequency acoustic propagation for the frequency range of 8-50 kHz in a shallow water waveguide. Fig. 3 shows the environmental data collected during the Kauai Experiment for the period between July 1 and July 3, 2003.
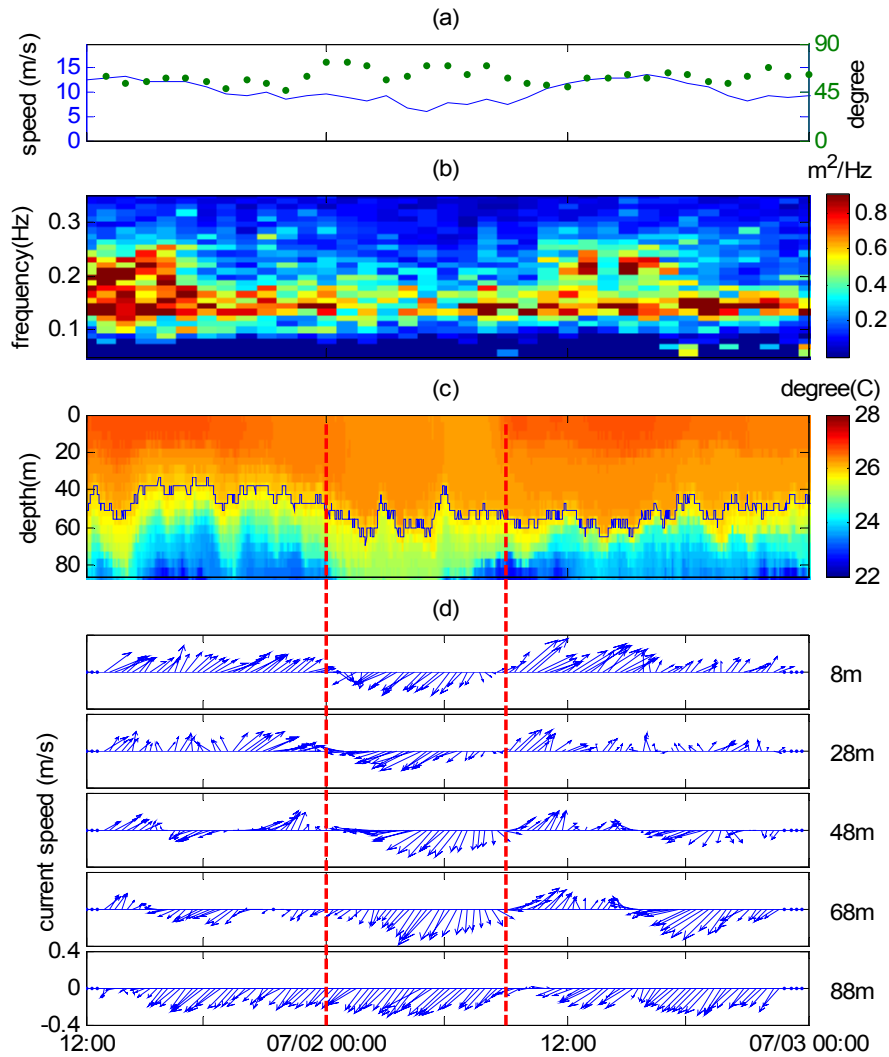


*Figure 3. Measured environmental parameters during Kauai Experiment from 07/01/2003 12:00 to 07/03/2003 00:00 GMT. (a) Wind speed and direction. (b) Surface wave spectrum (c) Temperature profile (d) Current profile at designated water depth (8,28,48,68,88 meters respectively).*

The wind field over the experiment site was generally steady in direction and speed, except for two time periods 07/01/2003 12:00 ~ 18:00 and 07/02/2003 12:00 ~ 18:00 GMT. The wind generated surface waves arrive at two different bands. First, there are larger scale waves formed after the wind has blown in the same direction for some duration of time (0.1-0.2 Hz), and then small scale surface chop (0.2-0.35 Hz) that appears almost immediately after wind speed increases and disappears shortly after wind speed decreases or changes direction (this is referred to as the land breeze effect). During 07/02/2003, 00:00 ~ 07/02/2003, 09:00 GMT (marked by red dash lines), a warm uniform southward current flow is shown in Fig. 3. While outside this window, the current is that of a stratified ocean (changed of direction somewhere between 28 to 48 meters). This roughly coincides with the thermocline shown by the blue line in Fig.3 (c).

The acoustic propagation results are shown for an array in upper water column. The APL array was moored in the upper water column between 22 and 36 meters from the sea surface and 1 Km from the source. A bottom mounted was at 3 Km away from the source. Fig. 4(a) shows the measured channel impulse response function for a hydrophone on the APL array. Different ray paths are indicated on the plot showing the direct (1), single bottom (2), and two surface bounced paths (3, and 4) respectively. In Fig. 4(b) corresponding buoy data from a measured surface spectrum is shown for the same period. It is noticed that as expected for the rough sea surface, the energy of the surface bounced paths decrease.
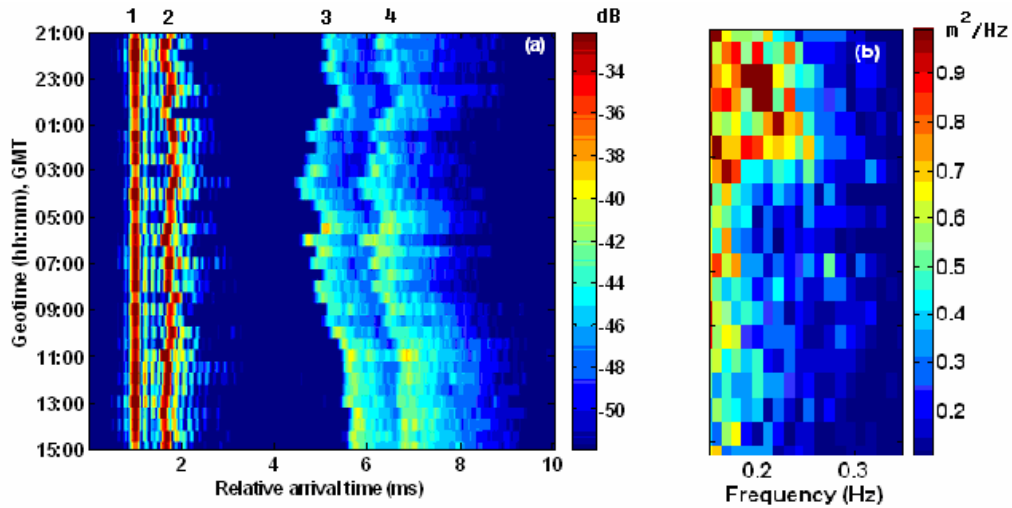


*Figure 4. (a) Channel impulse response function versus geotime on the APL array for the period of 21:00 on 7/1/2003 and 15:00 on 7/2/2003 GMT. Different arrival paths are numbered as direct (1), single bottom (2); single surface (3), bottom-surface (4). (b) Measured surface wave spectrum by a wave rider buoy.*

While the arrival delay fluctuations during this time is due to the combined effects of temperature and current profile changes shown in Fig. 3(c) and (d). The variability of the surface bounced energy is more pronounced for the bottom mounted array. The beamformed time-angle results of received signal on an eight element hydrophone array show a more dynamic behavior of the surface reflected energy [3].

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To further process the communication data form the Kauai Experiment, we have developed a multi-channel maximum *a posteriori* probability (MAP) receiver to take advantage of the sparse property of the channel. The MAP receiver employs the concept of sum product algorithm, or belief propagation algorithm for Bayesian networks [4], to compute *a posteriori* probability of the transmitted symbols [5]. By doing so, the receiver has achieved significant performance improvement with respect to existing receivers, at a cost of moderate complexity increase [6]. Figure 5 shows the symbol index versus the soft modulation results for the APL receiver array.



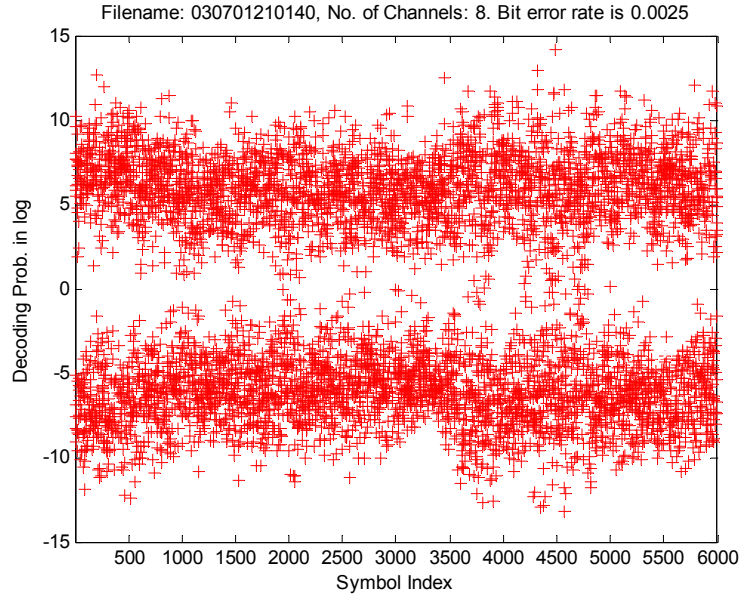Filename: 030701210140, No. of Channels: 8. Bit error rate is 0.0025

*Figure 5. Decoded multi-channel MAP receiver results of BPSK signal received by APL array during the Kauai experiment, at 21:01:40, July 01, 2003. By using 8 hydrophones, the achieved BER is 0.2% [7].*

**IMPACT/APPLICATIONS**

The low frequency band research benefits the science of understanding the sound propagation mechanism in a complex shallow water environment. For the high frequency band research there is a potential impact for acoustic tomography and for development of new systems with better decoding efficiency in underwater communication.

**RELATED PROJECTS**

The low frequency acoustic propagation part of our research on interaction of acoustic signal with shallow water internal waves is closely related to the recent and planned shallow water environment field work (such as AsiaEx and SW06). We have continued to work closely with J. Lynch (WHOI) B. Katsnelson (Univ. of Veronezh), and W. Siegmann, RPI. The Mid to High Frequency propagation part of our research is in collaboration with a multi-institutional effort involving M. Porter (HLS Inc.), D. Rouseff (APL-UW), W. Hodgkiss (MPL-SIO), and other colleagues at SIO, Univ. of NH, SPAWAR, HLS Inc., and NURC.

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